Data Reconciliation in a Heat Exchanger Network

by

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14553

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

JANUARY 2014

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Chemical Engineering Programme
Universiti Teknologi PETRONAS
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BACHELOR OF ENGINEERING (Hons)
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Approved by,

____

(Assoc. Prof. Dr. Marappagounder Ramasamy)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2014

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD IQRAM BIN NOOR AZMAN

ACKNOWLEDGEMENT

First of all, I would like to express my deepest gratitude to almighty God, the Most Merciful and Compassionate for blessing me strength, health and willingness to prevail and finish this project.

I would like to thank my supervisor Assoc. Prof. Dr. Marappagounder Ramasamy for accepting me under his supervision and providing guidance, encouragement and ideas to assist me accomplish this project. It was him who introduced me in the field of data reconciliation of crude preheat train in refinery industry and continued to help me in every stage to obtain deep knowledge in this field. Furthermore, my utmost appreciation and gratitude is also extended to him for the dedication of his time and effort for teaching and guiding me despite his other commitments.

A very special note of appreciation goes to my lovely family for their constant help, encouragement and supports throughout the period of performing this project. I would like to express my gratefulness to my chemical engineering colleagues for contributing and sharing ideas throughout the project been done in UTP.

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CHAPTER 1

INTRODUCTION

1.1 Background

In any modern chemical plant, petrochemical process or refinery, variables such as flow rates, temperatures, pressures, levels and compositions are routinely measured and recorded for the purpose of process control, on-line optimization or process economic evaluation (Romagnoli, J. A. R., & Sanchez, M. C., 2000). The quality of such process data significantly affects the performance and profit gained from the industrial processes. The same concept is applied in the process of crude preheating in any refinery industry where the crude oil is heated by passing it through a network of heat exchangers.

However, the measurement values which consist of inlet and outlet temperatures and flow rates resulting from the observations do not provide consistent information, since they contain some type of errors, either random measurement errors or gross biased errors. This means that the conservation equations (mass and energy), the common functional model chosen to represent operation at steady state are not satisfied exactly (Narasimhan, S., & Jordanche, C., 2000).

Therefore, nowadays it is such a common practice in any refinery plants to implement a technique to rectify the measurement data which is known as data reconciliation. This technique allows adjustment to be made on the measurement values so that corrected measurements can be produced which are consistent with the corresponding material and energy balance equation (Crowe, C.M., 1996).

Therefore, this report will discuss on the implementation of data reconciliation for measurement data or parameter involved in the heat exchanger network with in depth focus in crude preheat process in petroleum refinery plant. This approach will involve a set of mathematical model to be applied on the process instrumentation and observable measurements involved in heat exchanger network.

1.2 Problem Statement

In any chemical process, the validity of data measurement is very crucial and this also applied in crude preheating process in refinery industry. However, measurement data of heat exchanger network are always corrupted and having some bias due to some errors. Such errors cause the law of conservation of mass and energy is not obeyed. As a result, the optimization practices using such measurements to determine the efficiency of such process will not necessarily provide result as predicted.

1.3 Objectives

The main purpose of this project is to propose an appropriate numerical solution technique to be applied to formulate data reconciliation problem around heat exchanger network in crude oil preheating process in refinery industry. Data reconciliation or adjustment helps to improve measurements in heat exchanger network operation hence increasing its efficiency in terms of the amount of heat recovered which in turn increase the efficiency of crude preheating process.

1.4 Scope of Study

The scope of study or main focus of this entire text is the procedure of data reconciliation on the measurement data in counter-current shell and tube heat exchanger network that operate in crude oil preheat train in refinery industry. Throughout the procedure, the approach of Bilinear Steady-State Data Reconciliation is chosen and implemented to deal with bilinear steady-state system as in heat exchanger network

(HEN). The parameters involved in data measurement are flow rates, temperatures and enthalpy.

CHAPTER 2

LITERATURE REVIEW

2.1 Data Reconciliation

Since measurements of process variables in heat exchanger network (HEN) such as flow rates and temperatures are not only subjected to measurement error, but also to process variability, any set of measurement will not obey the laws of conservation. Thus, the application of data reconciliation techniques is very important. Data reconciliation is the procedure where measured data are adjusted optimally so that the new values satisfy the conservation laws and other constraints (Crowe, C.M., 1996).

According to the previous research on the technique used in data reconciliation of HEN which is considered as bilinear steady state system, most of them implement the approach proposed by Crowe et al and Swartz in which an approach namely QR Factorization is used. A Projection Matrix is developed by the approach which is utilized for decomposition. This is due to the fact that in HEN, there are two kind of data measurement need to be treated which are measured and unmeasured data.

Usually, in the design of any chemical processes, not all measuring instruments such as flow and temperature transducer are placed in all of the process streams. Even though it is a norm that unmeasured variables are eliminated from the set of constraint before reconciliation is carried out, some of the unmeasured process variables called observable or determinable unmeasured variables are not inferred in the procedure of data reconciliation. After the measured variables are reconciled, the observable unmeasured variables are estimated through calculation (Crowe, C.M., 1996). Hence, to avoid meaningless estimate of unmeasured variables, it is important to distinguish between the one that is observable and unobservable. There goes the need of classification of data measurement before reconciliation procedure is applied.

The original idea of eliminating determinable unmeasured variables was first introduced by Vaclavek where the reconciliation procedure is only based on a reduced subset of equations and measurements. Basically, the idea consists of classifying process variables and eliminates the non observable or indeterminable unmeasured variables in the general problem, so that the subset of equation only involves the measured variables. This is known as a process of decomposition where it helps to reduce the dimensionality of the problem (Romagnoli, J.A.R., & Sanchez, M.C., 2000).

In data reconciliation, the adjustment of measurements to compensate for random errors involves the resolution of a constrained minimization problem, known as least squares constraint. Both mass and energy balance equations are included also in the constraints. They can be linear but are generally nonlinear but for this project, the bilinear constraint is used which consist of linear and nonlinear constraints. The objective function is usually quadratic with respect to the adjustment of measurements, and it has the covariance matrix of measurements errors as weight. The objective function is known as general weighted sum of squares (Romagnoli, J.A.R., & Sanchez, M.C., 2000).

2.2 The Importance of Data Reconciliation

The justification of benefits for data reconciliation comes from many important applications as listed below:

One of the applications of data reconciliation is in evaluating process yield or in assessing consumption of utilities in heat exchanger units. Reconciled values provide more accurate estimates as compared to the use of raw data measurements (Narasimhan, S., & Jordanche, C., 2000). For example, a refinery-wide material balance reconciliation helps in a better estimate of overall refinery yields.

Instead, data reconciliation is useful in scheduling maintenance of the heat exchangers. The data can be used as key performance parameters of heat exchanger network (Narasimhan, S., & Jordanche, C., 2000). For instance, the heat transfer coefficient of heat exchangers can be used as estimation whether the heat exchangers need to be cleaned or not. The heat recover for the crude preheat process also known.

Moreover, many advanced control strategies require accurate estimates of controlled variables. Dynamic data reconciliation techniques can be used to derive accurate estimates for better process control (Narasimhan, S., & Jordanche, C., 2000). In the case of crude preheating process in heat exchanger network, the reconciled values of flow rates and enthalpy of crude as well as the hot stream helps in control strategy techniques in order to make sure that high amount of heat recovery and efficiency can be achieved.

2.3 Linear Steady-State Data Reconciliation

In any refinery plant, the crude oil is initially heated by passing it through an interconnected set of heat exchangers known as crude preheat train before being heated again in a furnace and fractionated by distillation column. The process streams that are used for heating the crude are the various product and pump-around streams from a downstream atmospheric or vacuum crude distillation column (Narasimhan, S., & Jordanche, C., 2000).

In order to maximize energy recovery from these process streams, the optimal flows of the crude splits through the different parallel heat exchanger trains should be determined online. For determining the optimal flows, the total inlet flow of crude and all process hot streams along with their inlet and outlet temperatures have to be specified. Generally, in crude preheat train, all the stream flows, as well as intermediate temperatures are measured. However, since all measurements contain errors, any optimization exercise carried out using such measurements will not necessarily result in the predicted gains. In order to overcome this, steady state reconciliation is applied to measurement data and eliminate measurements containing errors and obtain reconciled estimates of all stream flows and temperatures which satisfy the flow and enthalpy balances of the crude preheat train (Narasimhan, S., & Jordanche, C., 2000).

Two situations arise in linear data reconciliation. Sometimes all the variables included in the process model are measured, but more frequently some variables are not measured.

2.3.1 Data Reconciliation of Linear Systems with all variables measured

This is the simplest data reconciliation problems as we assumed that all variables let say flow rates are directly measured. It is also assumed that the measurements do not contain any systematic biases but only contain unknown random errors (Romagnoli, J. A. R., & Sanchez, M. C., 2000). For that reason, the inlet and outlet temperatures as well as the flow rates in the HEN are not balance and do not obey the laws of conservation of mass and energy. Hence, minor adjustment need to be made in order to make them consistent with both mass and energy balances (Lid, T., Strand, S. et al., 2000).

Let the measurements model described as follow

$$y = x + \varepsilon \text{ ....(1)}$$

where y is a (n x 1) vector of measured variables, x is a (n x 1) vector corresponding to the reconcile value of the measured variables, and ε is a (n x 1) vector of random variables. The measurement errors are assumed to be normally distributed with zero mean and known covariance.

Since the measured values contain random errors, let the constraint represented in general by

$$A_x = 0 \text{ ....(2)}$$

where A is a matrix of dimension m x n, and 0 is a m x 1 vector whose elements are zero. Each row of equation (2) corresponds to a constraint.

It is desired to derive estimates of the flow rates and temperature. Intuitively, we can impose the condition that the differences between the measured and estimated or reconciled values which also referred to as an adjustment, should be as small as possible. This objective function can be represented as

$$\min_x (y - x)^T W (y - x) \text{ ....(3)}$$

It is a least-square criterion. The n x n matrix W is usually a diagonal matrix, which represent the weight. The weight reflects the accuracy of the respective measurements. More accurate measurements are given larger weights in order to force their adjustments to be as small as possible. Generally, it is assumed that the error variances for all measurements are known and the weights are chosen to be the inverse of the covariance matrix Σ. Therefore equation (3) is changed as

$$\min_x (y - x)^T \Sigma^{-1} (y - x) \text{ ....(4)}$$

Consider the case when all data variables are measured, the analytical solution or estimates obtained through data reconciliation are given by.

$$\hat{x} = y - \Sigma A^T (A \Sigma A^T)^{-1} A y \text{ ....(5)}$$

where $\hat{x}$ is denoted as the solution for the estimates or reconciled value. It is assumed that matrix A is not linearly dependent on equation (2). The estimates given by equation (5) satisfy the constraint.

2.3.2 Data reconciliation of Linear Systems with measured and unmeasured variables

Crowe et al. introduced the use of projection methods for data reconciliation which was later extended to non-linear systems by Swartz. Swartz proposed an iterative procedure to reconcile data by applying QR factorization introduced by Crowe et al (Ijaz, H., et al., 2013). It can be applied in data reconciliation by:

i) Reconciling flows first

ii) Computing enthalpy for each heat exchanger in the network based on the measured inlet and outlet temperature values.

iii) Reconcile the enthalpy values

iv) Recalculate back the temperature values according to the reconciled value of enthalpy.

Partially measured processes are solved by decomposing the reconciliation problem into two sub-problems. In the first sub-problem, all the measured variables are reconciled, followed by the calculation of the unmeasured variables. Let the variables be classified into two sets, measured variables x and unmeasured variables u. Then a set of linear balance equations for a steady state process can be written as follow

$$A_x x + A_u u + 0 \quad ....(6)$$

where u is a (p x 1) vector of unmeasured variables, x is a (n x 1) vector of measured variables and A_x (m x n), A_u (m x p) are matrices of known constants.

The presence of measurement errors does not allow the balance equations to be satisfied exactly. Therefore, the data reconciliation problem must solve the following least-square problem

$$\min_x (y - x)^T \Sigma^{-1} (y - x)$$

$$\text{s.t.} \quad A_x x + A_u u + 0 \quad \text{..........(7)}$$

The unmeasured variables u and A_u in equation (7) are eliminated by a projection matrix, P to solve the reconciliation problem. This is made possible by pre-multipying matrix A_u with P, which has the property of

$$P_A u = 0 \quad \text{..........(8)}$$

Thus, the reduced set of constraints involving only measured variables is the following

$$PA_x x = 0 \quad \text{..........(9)}$$

The reduced data reconciliation problem is to minimize the objective function in equation (7) subject to the constraints, equation (9)

$$\min_x (y - x)^T \Sigma^{-1} (y - x)$$
$$\text{s.t.} \quad PA_x x = 0 \quad \text{..........(10)}$$

Since the constraints are similar to equation (2), the reconciled values for x can be obtained by using the equation (5) with the matrix A_x being replace by the reduced matrix PA_x

$$\hat{x} = y - \Sigma(PA_x)^T[(PA_x)\Sigma(PA_x)^T]^{-1}(PA_x)y \quad \text{..........(11)}$$

The solution $\hat{x}$ can be substituted in equation (8) to obtain the estimates û for the variable u provided that the unmeasured variables are determinable.

$$\hat{u} = -\left(A_u{}^T A_u\right)^{-1} A_x\, x\hat{} \quad \text{..........(12)}$$

2.4 Bilinear Steady-State Data Reconciliation

In this project where the objective is to reconcile data in heat exchanger network, steady state data reconciliation specifically for bilinear system is utilized. This is due to the fact that HEN involves multi-components data to be reconciled in which one of the constraints is the product of two variables. The constraint here is the value of enthalpy which is a function of temperature and flow rate. Both flow rate and enthalpy values are reconciled simultaneously.

Bilinear system is actually a type of non-linear system. Bilinear steady-state data reconciliation technique is used to treat this bilinear system because it is more efficient than using non-linear programming technique to solve for the non-linear data reconciliation problems. Such technique also has been used due to the fact that a significant number of industrial applications deal with multicomponent systems. However, the disadvantage of this method is that it cannot handle inequality constraints such as simple bounds on variables. As a result in some cases, this technique may give negative estimates to the measurement data (Narasimhan, S., & Jordanche, C., 2000).

2.4.1 Modification of Bilinear Constraints

Throughout this section, the treatment of general multi component and energy (bilinear) reconciliation problems by using the QR decomposition approach is discussed. The procedure involve in data reconciliation of bilinear multicomponent and energy balance in this section is according to Romagnoli, J. A. R., and Sanchez, M. C., (2000) through a book entitled "Data Processing and Reconciliation for Chemical Process Operation".

Component mass and energy balance as well as normalization equations which are the constraints for reconciliation procedure of enthalpy data are written by using the method for bilinear system. Streams are divided into three categories depending on the combination of flow rates (F) and temperature (T) measurements as shown in *Table 1.*

Table 1: Categories of steams

Category	F	T
1	Measured	Measured
2	Unmeasured	Measured
3	Measured/Unmeasured	Unmeasured

However, in this case study, only the first two categories are taken into consideration.

Bilinear Constraints:

a) Component mass/energy balances:

$$B_1 f_{ch} + B_2 V d = 0 \quad \text{.................(13)}$$

b) Normalization equations:

$$E_1 f_{ch} + E_2 V d + E_4 f_m + E_5 f_u = 0 \quad \text{.................(14)}$$

Where f_{ch} : vector of enthalpy flows for stream in Category 1

d : vector of measured temperatures for streams in Category 2

f_m : measured total flow rates

f_u : unmeasured total flow rates

V : diagonal matrix of unmeasured total flow rates of Category 2

The measured variable d is replaced by a consistent measured value with the correction factor ε_d as follows,

$$d = d' + \varepsilon_d \quad \text{.....................(15)}$$

A new variable, θ is created which defined as

$$\theta = V_{\varepsilon_d} \quad \text{......................(16)}$$

The variable d in the terms that appear in equation (13) and (14) are replaced by

$$B_2 V d = B_2 \theta + B_2 V d' \quad \text{................(17)}$$

$$E_2 V d = E_2 \theta + E_3 V d'$$

The unmeasured total flow rates of a stream with specific flow rates of Category 2 is to be displayed by introducing matrices B_4 and E_6 as

$$B_2Vd = B_4(d)f_{u_2} \quad \text{.................(18)}$$
$$E_2Vd = E_6(d)f_{u_2}$$

New matrices of B_5 and E_7 are obtained as follow to group all unmeasured total flow rates by adding zero columns to B_4 and E_6.

$$B_5(d')f_{u_2} = B_2Vd' \quad \text{................(19)}$$
$$E_7(d')f_{u_2} = E_2Vd'$$

The set of energy balances and normalization equation after all the above mentioned modification of the bilinear terms are now written as:

$$\begin{bmatrix} 0 & B_1 & B_2 & B_5 \\ E_4 & E_1 & E_2 & E_8 \end{bmatrix} \begin{bmatrix} f_m \\ f_{ch} \\ \theta \\ f_u \end{bmatrix} = 0 \qquad \text{where, } E_8 = E_7 + E_5 \quad \text{..........(20)}$$

Considering adjustment of total flow rates (ε_f) and enthalpy flows (ε_{fch}), the above equation become

$$\begin{bmatrix} B_{11} & B_{22} \end{bmatrix} \begin{bmatrix} a \\ f_u \end{bmatrix} = 0, \quad \text{................(21)}$$

$$\text{where, } a = \begin{bmatrix} \varepsilon_{f_m} \\ \varepsilon_{f_{ch}} \\ \theta \end{bmatrix},\ B_{11} = \begin{bmatrix} 0 & B_1 & B_2 \\ E_4 & E_1 & E_2 \end{bmatrix},\ B_{22} = \begin{bmatrix} B_5 \\ E_8 \end{bmatrix} \quad \text{..........(22)}$$

Therefore, the general reconciliation problem can be written as:

$$\min_{\delta,\theta}\left(\varepsilon_{f_m}{}^T\Psi_{f_m}{}^{-1}\varepsilon_{f_m} + \varepsilon_{f_m}{}^T\Psi_{f_{ch}}{}^{-1}\varepsilon_{f_{ch}} + \theta^T\Psi_\theta{}^{-1}\theta\right) \text{.........(23)}$$
$$\text{s.t. } \begin{bmatrix} B_{11} & B_{22} \end{bmatrix} \begin{bmatrix} a \\ f_u \end{bmatrix} = -\begin{bmatrix} 0 & B_1 \\ E_4 & E_1 \end{bmatrix} \begin{bmatrix} f_m \\ f_{ch} \end{bmatrix} = e$$

Σ_{fm}, Ψ_{fch} and Ψ_θ are the weighing matrices for f_m, f_{ch} and θ. Ψ_θ is defined as

$$\Sigma_\theta = V\Sigma_d V \quad \text{.............(24)}$$

CHAPTER 3

METHODOLOGY

3.1 Project Flow Chart

Basically, this is the flow of the project right from the beginning until data reconciliation technique is applied to adjust the respective measurement data in HEN.

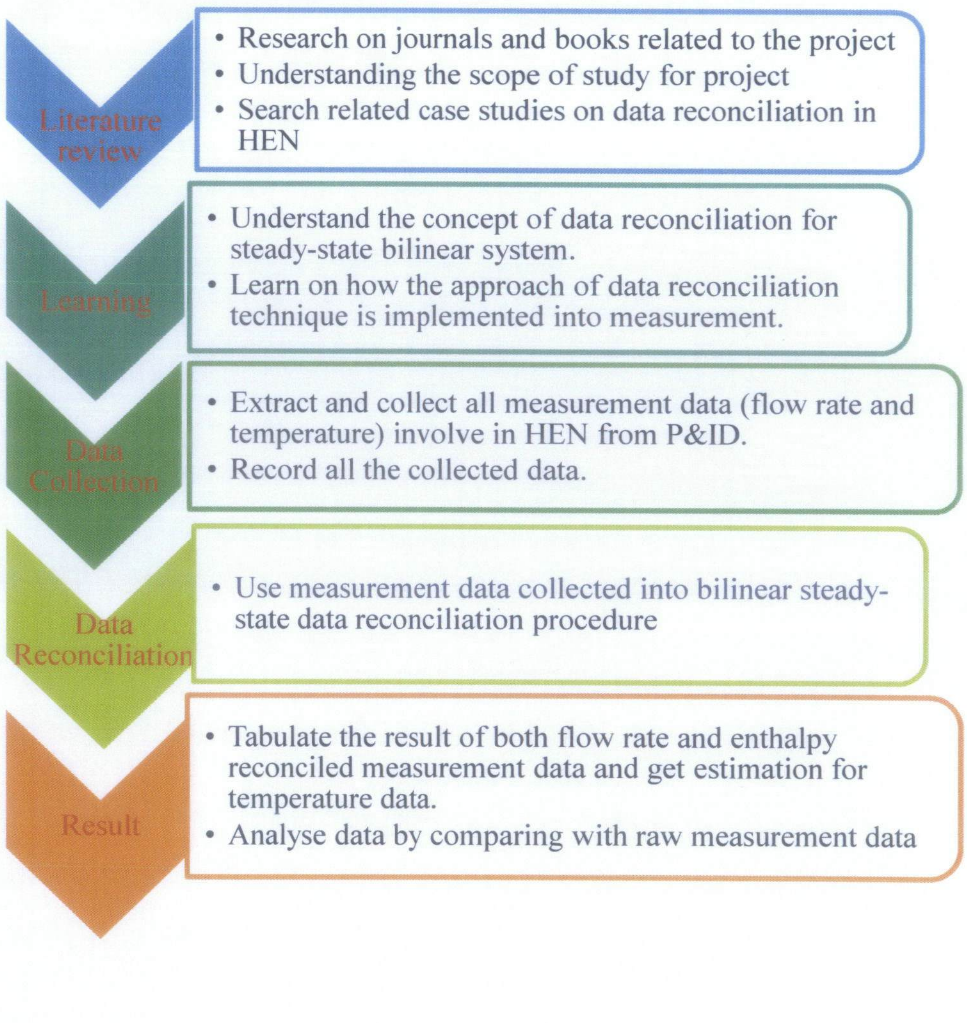

Figure 1: Project Flow

3.2 Gantt Chart and Key Milestone

This is the suggested gantt chart prepared by the writer for the fulfillment of the project for both FYP1 and FYP2. The suggested key milestone by the coordinator in order to keep the progress of the project with the allocated time frame is also included.

Table 2: Timeline for FYP1

No	Detail Work	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic															
2	Consultation with SV on project title details															
3	Preliminary Research Work															
4	Preparing Extended Proposal and consultation with SV															
5	Submission of Extended Proposal Defence															
6	Preparation for proposal defence • Preparing slide presentation															

7	Proposal Defence														
8	Extract measurements data of HEN from P&ID (flow rates and temperatures tags) and tabulated in excel														
9	Preparation of Interim Draft Report														
10	Submission of Interim Draft Report														
11	Submission of Interim Report														

Process

Suggested Milestone

Table 3: Timeline for FYP2

No	Detail Work	1	2	3	4	5	6	7		8	9	10	11	12	13	14	15
1	Get the exact values of measurement tag in numbers																
2	Data Reconciliation																
3	Submission of Progress Report																
4	Data Reconciliation Continues																
5	Pre-SEDEX																
6	Submission of Draft Report																
7	Submission of Dissertation (soft bound)																
8	Submission of Technical Paper																
9	Oral Presentation																
10	Submission of Project Dissertation (Hard Bound)																

3.3 Project Activities

3.3.1 Final Year Project 1

Heat Exchanger Network (HEN) Measurement Data Extraction

a. Review the given Piping and Instrumentation Diagrams (P&ID) of crude preheat process.
b. Go through all the process involve and identify some of the heat exchangers that are going to be used and focused on in the case study.
c. Go through all the inlet and outlet streams connecting the heat exchangers which form the network. The variables or parameters which are in focus are both the flow rates and temperatures.
d. Extract all both inlet and outlet flow rates and temperatures tags for each of the heat exchanger and transform them into microsoft visio representation with inlet and outlet streams connected to one another heat exchangers and all streams are labelled with available tag of flow rates and temperatures as in *Figure 3.*
e. Identify both measured and unmeasured variables.
f. At the same time all the temperatures and flow rates measurements tags are tabulated in microsoft office excel as in *Table 3.*

3.3.2 Final Year Project 2:

Heat Exchanger Network (HEN) Measurement Data Collection from Refinery Plant

Based on the extracted data of heat exchanger network in the form of tag numbers, the raw measurement data in values for both flow rate and temperature are collected from a refinery plant. The properties of crude oil and hot streams are also collected from refinery plant. All the measurement data are recorded in *Table 5 and Table 6* and will be used for bilinear steady-state data reconciliation procedure.

Bilinear Steady-State Data Reconciliation Procedure

The proposed bilinear steady-state data reconciliation model approach is applied to the raw measurements data of HEN.

a) Calculation of specific enthalpy:

   From the available data of heat capacity, C_p for all the hot streams and crude and also the value of temperature, specific enthalpy, H is calculated by the equation of,

$$H = C_pT$$

b) Calculation of enthalpy:

   Value of enthalpy for both hot and cold streams for each heat exchanger unit are calculated by using the equation of

$$Q = FC_pT$$

c) Simultaneous data reconciliation of flow rate and specific enthalpy to satisfy energy balance or enthalpy balance:

   i. Apply the bilinear steady-state data reconciliation mathematical model to all of the flow rates measurement and calculated enthalpy data to reconcile data measurement on flow rates and enthalpy for the HEN.

   ii. The result of reconciled values of both flow rate and enthalpy is well tabulated for comparison with the raw data of flow rate and calculated value of enthalpy.

d) Recalculation of temperatures:

   i. From the reconciled values of enthalpy and flow rate, recalculate back the value of inlet and outlet temperatures for each of heat exchanger unit.

3.4 Project Description

Throughout the project, a total of 44 streams and 14 counter-current shell and tube heat exchangers in series and parallel are involved in the crude preheat train process which are in focus for the case study. The variables involved are 44 flow rates and 44 temperatures. By referring to Piping and Instrumentation Diagram (P&ID) of the process, all the measurements data involve in the process of recovering heat are collected and recorded. In this process the data collected are the inlet and outlet temperatures as well as the inlet and outlet flow rates of hot and cold streams. The cold streams consist of crude oil while the hot streams used to heat the crude oil consist of light kerosene, kerosene, atmospheric gas oil (AGO), diesel, top pump around (TPA) and Low Sulfurous Waxy Residue (LSWR).

The block diagram below in *Figure 2* shows a sample of one counter-current shell and tube heat exchanger used in the crude preheat process with the inlet and outlet temperature and flow rates data measurement extracted from P&ID.

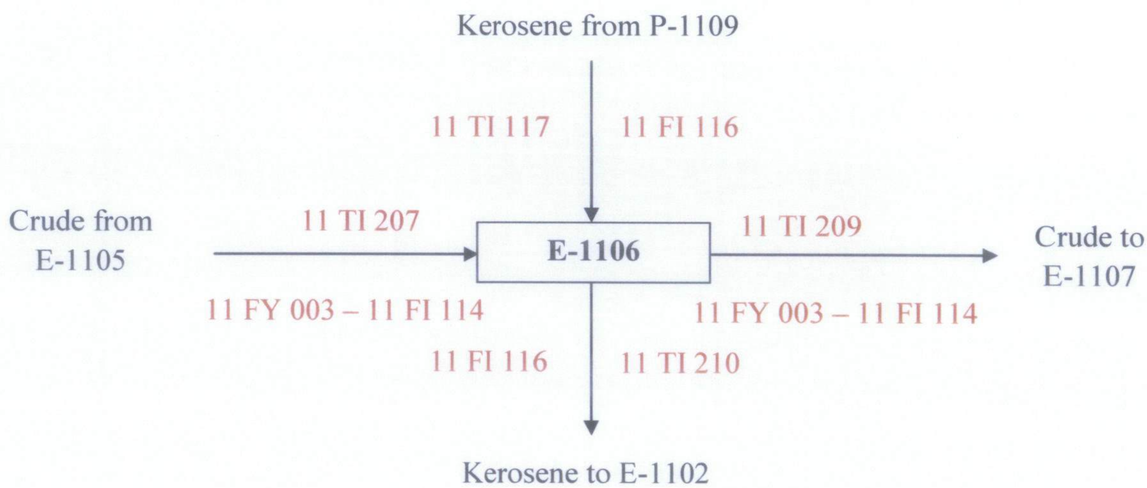

Figure 2: Sample model of a heat exchanger unit

This is heat exchanger E-1106. TI and FI correspond for the tag of "Temperature Indicator" and "Flow Indicator".

3.5 Tools and Equipments

Throughout the flow of the project the tools and equipments required are as follow:

- Microsoft Excel – Heat Exchanger Network Data recording and analysis
- Microsoft Visio – Development of Heat Exchanger Network (HEN) representation
- Microsoft Word – Report writing
- MATLAB – Solving matrix form of mathematical model to produce reconciled data.
- PETROSIM – Simulation software to generate properties of crude oil and products streams.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Data Gathering

4.1.1 Heat Exchanger Network (HEN) Representation of Crude Preheat Train

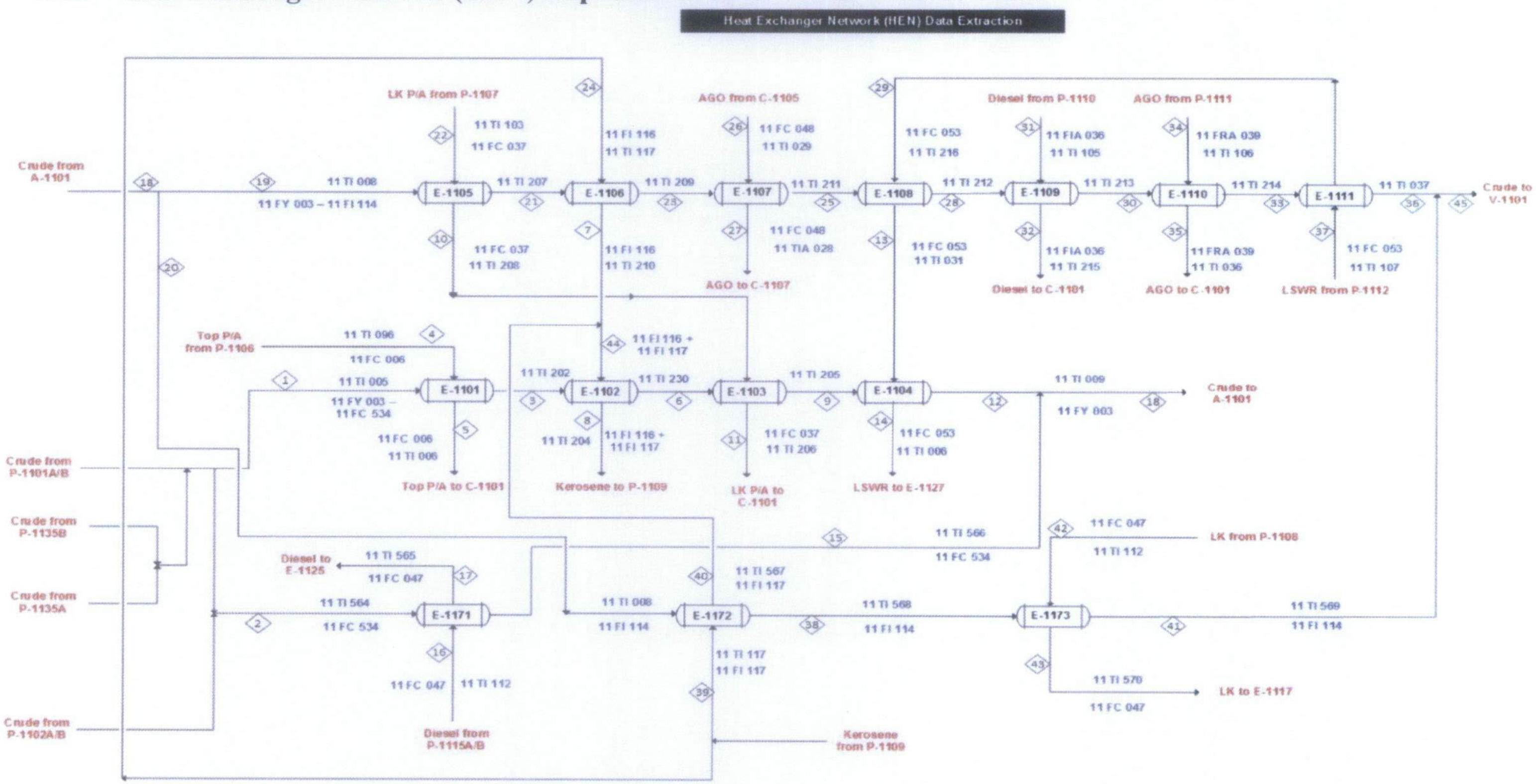

Figure 3: Heat Exchanger Network in Crude Preheating Process

Figure 3 above shows the whole system of heat exchanger network involve in the project. A total of 14 heat exchanger units in parallel and series with a total number of 44 process streams are involved. All the raw measurement data available as well as the determinable unmeasured data of temperatures and flow rates are treated by the bilinear steady-state data reconciliation model.

4.1.2 Heat Exchanger Network Data Measurement

Table 4 below shows all the raw measurement data tags extracted from Piping and Instrumentation Diagrams (P&ID) of crude preheating process that include the inlet and outlet flow rates and temperatures of both cold and hot streams in all the heat exchanger unit.

Table 4: HEN Data Extraction

Stream No.	Flow Rate Tags	Temperature Tag
1	11 FY 003 – 11 FC 534	11 TI 005
2	11 FC 534	11 TI 564
3	-	11 TI 202
4	11 FC 006	11 TI 096
5	-	11 TI 006
6	-	11 TI 230
7	-	11 TI 210
8	-	11 TI 204
9	-	11 TI 205
10	-	11 TI 208
11	-	11 TI 206
12	-	-
13	-	11 TI 031
14	11 FC 053	11 TI 006
15	-	11 TI 566
16	11 FC 047	11 TI 112
17	-	11 TI 565
18	11 FY 003	11 TI 009
19	11 FY 003 – 11	11 TI 008

	FI 114	
20	11 FI 114	11 TI 008
21	-	11 TI 207
22	11 FC 037	11 TI 103
23	-	11 TI 209
24	11 FI 116	11 TI 117
25	-	11 TI 211
26	11 FC 048	11 TI 029
27	-	11 TIA 028
28	-	11 TI 212
29	-	11 TI 216
30	-	11 TI 213
31	-	11 TI 105
32	11 FIA 036	11 TI 215
33	-	11 TI 214
34	11 FRA 039	11 TI 106
35	-	11 TI 036
36	-	11 TI 037
37	-	11 TI 107
38	-	11 TI 568
39	11 FI 117	11 TI 117
40	11 FI 117	11 TI 567
41	-	11 TI 569
42	11 FC 047	11 TI 112
43	11 FC 047	11 TI 570
44	-	-

4.2 Classification of Heat Exchanger Network Measurement Data

From the extracted data in tag numbers, all the raw measurement data for both flow rate and temperature in HEN in real value have been collected from a refinery plant. From all the collected flow rates and temperature raw measurement data, the classification of measurement data involved in the whole set of heat exchanger network are done. The measurement data are classified as follows:

a. Measured Variables:
   - Redundant (overmeasured): A measured process variable that can also be computed from the balance equations and the rest of the measured variables
   - Non-redundant (just measured): A measured variable that cannot be computed from the balance equations and the rest of the measured variables.

b. Unmeasured Variables:
   - Determinable: An unmeasured variable is determinable if it can be evaluated from the available measurements using balance equations.
   - Indeterminable: An unmeasured variable is indeterminable if cannot be evaluated from the available measurements using balance equations.

i. Flow rate Data:

The data on flow rate are classified in two categories which are "non redundant measured variables" and "determinable unmeasured variables".

a. Nonredundant Measured variables of Flow Rate:

   There are 15 measured variables of flow rate as follow:

   $F_1, F_2, F_4, F_{14}, F_{16}, F_{18}, F_{19}, F_{20}, F_{22}, F_{24}, F_{26}, F_{32}, F_{34}, F_{39}, F_{42}$

   The collected raw measurement data of flow rates from refinery plant are originally in the unit of m^3/h. For the purpose of data reconciliation, they are converted into kg/h unit by multiplying with the value of density of crude and product streams involve around each heat exchanger unit. This crude and product streams property is obtained from simulation by using PETROSIM software from refinery plant. The details on data measurement of flow rate can be refered to *Appendix 2*.

b. Determinable unmeasured variables:

   There are 29 determinable unmeasured variables of flow rate and are listed as follow

   $F_3, F_5, F_6, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13}, F_{15}, F_{17}, F_{21}, F_{23}, F_{25}, F_{27}, F_{28}, F_{29}, F_{30}, F_{31}, F_{33}, F_{35}, F_{36}, F_{37}, F_{38}, F_{40}, F_{41}, F_{43}, F_{44}$

   Determinable unmeasured variables of flow rates are estimated from the reconciled values of measured flow rates as in each heat exchanger unit and assumption is made where the inlet flow rate of both hot and cold streams are the same with their outlet flow rates. They are determined as follow.

- $F_3 = F_6 = F_9 = F_{12} = \boldsymbol{F_1}$
- $F_5 = \boldsymbol{F_4}$
- $F_7 = \boldsymbol{F_{24}}$
- $F_8 = F_{44} = F_7 + F_{40} = \boldsymbol{F_{24}} + \boldsymbol{F_{39}}$
- $F_{11} = F_{10} = \boldsymbol{F_{22}}$
- $F_{13} = F_{29} = F_{37} = \boldsymbol{F_{14}}$
- $F_{15} = \boldsymbol{F_2}$
- $F_{17} = \boldsymbol{F_{16}}$
- $F_{21} = F_{23} = F_{25} = F_{28} = F_{30} = F_{33} = F_{36} = \boldsymbol{F_{19}}$
- $F_{38} = F_{41} = \boldsymbol{F_{20}}$
- $F_{40} = \boldsymbol{F_{39}}$
- $F_{43} = \boldsymbol{F_{42}}$
- $F_{35} = \boldsymbol{F_{34}}$
- $F_{31} = \boldsymbol{F_{32}}$
- $F_{27} = \boldsymbol{F_{26}}$

ii. Temperature Data:

a. Nonredundant Measured variables of temperature:

From a total of 44 data measurement for temperatures, 42 data are classified as measured variable as shown below. The details on each measured temperature values can be refered to *Appendix 2*.

T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8, T_9, T_{10}, T_{11}, T_{13}, T_{14}, T_{15}, T_{16}, T_{17}, T_{18}, T_{19}, T_{20}, T_{21}, T_{22}, T_{23}, T_{24}, T_{25}, T_{26}, T_{27}, T_{28}, T_{29}, T_{30}, T_{31}, T_{32}, T_{33}, T_{34}, T_{35}, T_{36}, T_{37}, T_{38}, T_{39}, T_{40}, T_{41}, T_{42}, T_{43}

b. Determinable unmeasured variables of temperature:

T_{12} *and* T_{44}

They are determined as follow.

$$T_{12} = \frac{[(F_{12} + F_{15})(C_{p18}T_{18}) - F_{15}C_{p15}T_{15}]}{F_{12}C_{p12}}$$

$$= \frac{[(F_2 + F_2)(C_{p18}T_{18}) - F_2C_{p15}T_{15}]}{F_1C_{p12}}$$

$$T_{44} = \frac{[(F_{40}C_{p40}T_{40}) + (F_7C_{p7}T_7)]}{(F_7C_7 + F_{40}C_{p40})}$$

$$= \frac{[(F_{39}C_{p40}T_{40}) + (F_{24}C_{p7}T_7)]}{(F_{24}C_{p7} + F_{39}C_{p40})}$$

All the value of determinable unmeasured variables of flow rates and temperatures are estimated and obtained from the reconciled values of flow rates and estimated value of temperatures resulting from the treatment of all the measured raw measurement data of flow rates and calculated enthalpies by using the Bilinear Steady-State Data Reconciliation Model in terms of matrices. The calculation has already been shown but correlated with all the mass and energy balance as in *Appendix 1*.

4.3 Bilinear Steady-State Data Reconciliation Model

The mathematical model involve in Bilinear Steady-State Data Reconciliation for HEN are developed in a set of matrices.

4.3.1 Least squares problem

The objective function or data reconciliation problem to solved in the form of least square criterion is given by

$$\mathbf{min}_{\boldsymbol{x}}(\boldsymbol{y}-\boldsymbol{x})^{T}\boldsymbol{V}^{-1}(\boldsymbol{y}-\boldsymbol{x})$$

$$\mathbf{min}\ \begin{bmatrix}\hat{\mathrm{F}}\\ \hat{\mathrm{Q}}\end{bmatrix}=\left(\begin{bmatrix}\mathrm{F}\\ \mathrm{Q}\end{bmatrix}-\begin{bmatrix}\hat{\mathrm{F}}\\ \hat{\mathrm{Q}}\end{bmatrix}\right)^{\mathrm{T}}\mathrm{V}^{-1}\left(\begin{bmatrix}\mathrm{F}\\ \mathrm{Q}\end{bmatrix}-\begin{bmatrix}\hat{\mathrm{F}}\\ \hat{\mathrm{Q}}\end{bmatrix}\right)$$

Subject to: $F_{Hi}-F_{Ho}=0$ $\quad$ $F_{Ci}-F_{Co}=0$ $\quad$ (Mass Balance)

$Q_{Ci}-Q_{Co}+Q_{Hi}-Q_{Ho}=0$ $\quad$ (Energy Balance)

Where $\hat{\mathrm{F}}$: Reconciled flow rate

$\hat{\mathrm{Q}}$: Reconciled Enthalpy

F: Raw flow rate measurement

Q: Calculated enthalpy

4.3.2 Analytical Solution

The analytical solution or final model of bilinear steady-state data reconciliation in order to treat all the measurement data around heat exchanger network of crude preheating process is developed as follow.

$$\hat{x} = x - VA^T(AVA^T)^{-1}Ax$$

Where $\hat{x}$: Vector of reconciled value of flow rate and calculated enthapy

x: Vector of raw measurement value of flow rate and calculated enthalpy

A: Incidence Matrix

V: Covariance Matrix (Diagonal Matrix)

a. Raw Measurement data vector matrix x:

x = [55 x 1] matrix

x = [F_1; F_2; F_4; F_{14}; F_{16}; F_{19}; F_{20}; F_{22}; F_{24}; F_{26}; F_{32}; F_{34}; F_{39}; F_{42}; F_1h_1; F_2h_2; F_1h_3; F_4h_4; F_4h_5; F_1h_6; $F_{24}h_7$; $F_{24}h_8$; F_1h_9; $F_{22}h_{10}$; $F_{22}h_{11}$; $F_{14}h_{13}$; $F_{14}h_{14}$; F_2h_{15}; $F_{16}h_{16}$; $F_{16}h_{17}$; $F_{19}h_{19}$; $F_{20}h_{20}$; $F_{19}h_{21}$; $F_{22}h_{22}$; $F_{19}h_{23}$; $F_{24}h_{24}$; $F_{19}h_{25}$; $F_{26}h_{26}$; $F_{26}h_{27}$; $F_{19}h_{28}$; $F_{14}h_{29}$; $F_{19}h_{30}$; $F_{32}h_{31}$; $F_{32}h_{32}$; $F_{19}h_{33}$; $F_{34}h_{34}$; $F_{34}h_{35}$; $F_{19}h_{36}$; $F_{14}h_{37}$; $F_{20}h_{38}$; $F_{39}h_{39}$; $F_{39}h_{40}$; $F_{20}h_{41}$; $F_{42}h_{42}$; $F_{42}h_{43}$]

x = [310443.55; 50494.52; 509386.23; 134207.07; 166282.19; 328996.67; 31941.40; 299434.14; 26122.56; 22121.27; 138153.45; 37470.72; 33854.98; 141069.53; 35922270000.92; 4651805969.52; 54451526337.64; 201926151544.65; 190027669247.11; 67073994919.03; 11479425361.12; 11852182958.03; 81277889844.20; 136301587020.18; 112542774119.03; 82235826195.85; 49368794422.99; 17217513979.08; 74384906353.56; 60077568963.57; 113383216182.30; 11008069750.62; 129002291785.86; 158125643931.14; 132784777922.03; 15531842462.12; 138084326038.62; 16353147674.74; 10044246514.74; 157981324051.92; 105847325913.75; 169778742322.45; 111247490592.47; 91475364593.33; 176518647005.01; 35726522918.92; 26478114505.88; 185169288847.28; 133009377544.36; 13705417020.73; 20129352146.36; 16468591001.96; 13940735254.34; 67783480670.24; 66866502722.94]

b. Incidence Matrix A:

A = [24 x 55] matrix

The elements involved in the incidence matrix A consist of the values of 1 and 0. For the simplicity, only the elements that have value of 1 are shown here which is denoted as a_{ij}. Where i represents the row and j represents the column in which the value of 1 is located in the matrix. All the elements involved are shown as below. The complete incidence matrix can be refered in the *Appendix 3*.

$a_{11} = 1 , a_{13} = 1$

$a_{24} = -1$

$a_{32} = 1, \ a_{35} = 1$

$a_{11} = 1 , a_{13} = 1$

$a_{32} = 1, \ a_{35} = 1$

$a_{46} = 1 , a_{48} = 1$

$a_{59} = 1$

$a_{6\,10} = 1$

$a_{7\,11} = -1$

$a_{8\,12} = 1$

$a_{97} = 1 , a_{9\,13} = 1$

$a_{10\,14} = 1$

$a_{11\,15} = 1 , a_{11\,17} = -1, \ a_{11\,18} = 1, \ a_{11\,19} = -1$

$a_{12\,17} = 1 , a_{12\,20} = -1, \ a_{12\,21} = 1, \ a_{12\,22} = -1$

$a_{13\,20} = 1 , a_{13\,23} = -1, \ a_{13\,24} = 1, \ a_{13\,25} = -1$

$a_{14\,23} = 1 , a_{14\,26} = 1, \ a_{14\,27} = -1$

$a_{15\,16} = 1\,, a_{15\,28} = -1,\; a_{15\,29} = 1,\; a_{15\,30} = -1$

$a_{16\,24} = -1\,, a_{16\,31} = 1,\; a_{16\,33} = -1,\; a_{16\,34} = 1$

$a_{17\,21} = -1\,, a_{17\,33} = 1,\; a_{17\,35} = -1,\; a_{17\,36} = 1$

$a_{18\,35} = 1\,, a_{18\,37} = -1,\; a_{18\,38} = 1,\; a_{18\,39} = -1$

$a_{19\,26} = -1\,, a_{19\,37} = 1,\; a_{19\,40} = -1,\; a_{19\,41} = 1$

$a_{20\,40} = 1\,, a_{20\,42} = -1,\; a_{20\,43} = 1,\; a_{20\,44} = -1$

$a_{21\,42} = 1\,, a_{21\,45} = -1,\; a_{21\,46} = 1,\; a_{21\,47} = -1$

$a_{22\,41} = -1\,, a_{22\,45} = 1,\; a_{22\,48} = -1,\; a_{22\,49} = 1$

$a_{23\,32} = 1\,, a_{23\,50} = -1,\; a_{23\,51} = 1,\; a_{23\,52} = -1$

$a_{24\,50} = 1\,, a_{24\,53} = -1,\; a_{24\,54} = 1,\; a_{24\,55} = -1$

c. **Covariance Matrix:**

i. Variance of flow rate:

Value of variance for flow rate is obtained by using standard deviation of 0.5% of measured values for all streams flow rate.

ii. Variance of temperature:

Value of variance for all temperature measurements are constant where for all the temperature streams, standard deviation of 0.75% of temperature range between 0 to 200 °C is used.

iii. Variance of enthalpy:

Variance for the calculated enthalpy for each heat exchanger unit is obtained by calculation using Taylor's series and is given as follow.

$Var(enthalpy) \approx (T\,*)^2 Var(F) + (F\,*)^2 Var(T)$

Where, Var (enthalpy): Variance of enthalpy

Var (F) : Variance of flow rate

Var (T) : Variance of temperature

T* : Temperature measurement

F* : Flow rate measurement

The covariance matrix for both flow rate and enthalpy are generated as follow

V = [55 x 55] diagonal matrix

The elements involved in the Covariance Matrix V consist of the values of Variance of flow rate and temperature. The rest are the large values of 0 in numbers. For the simplicity, only the elements that have value of calculated variance of flow rate and temperature are shown here which is denoted as V_{ij}. Where i represents the row and j represents the column in which the value of variance is located in the matrix. All the elements involved are shown as below. The complete incidence matrix can be refered in the *Appendix 3*.

$V_{11} = 602344.98$,$V_{22} = 15935.60$, $V_{33} = 1621714.59$,
$V_{44} = 112572.12$,$V_{55} = 172811.05$, $V_{66} = 676492.57$
$V_{77} = 6376.58$,$V_{88} = 560380.02$, $V_{99} = 4264.93$
$V_{10\,10} = 3058.44$,$V_{11\,11} = 119289.85$, $V_{12\,12} = 8775.34$
$V_{13\,13} = 7163.50$,$V_{14\,14} = 124378.83$, $V_{15\,15} = 55251658125.86$
$V_{16\,16} = 1451654734.38$,$V_{17\,17} = 56602052964.84$, $V_{18\,18} = 183601159627.15$
$V_{19\,19} = 179295200154.29$,$V_{20\,20} = 57839059644.72$,
$V_{21\,21} = 497090895.85$
$V_{22\,22} = 412896524.80$,$V_{23\,23} = 59538323317.52$, $V_{24\,24} = 65875236525.68$
$V_{25\,25} = 61771530756.92$,$V_{26\,26} = 15384843813.40$, $V_{27\,27} = 12445864698.04$
$V_{28\,28} = 1673261235.09$,$V_{29\,29} = 20858750881.94$, $V_{30\,30} = 19014000497.69$
$V_{31\,31} = 71251443749.12$,$V_{32\,32} = 671612035.94$, $V_{33\,33} = 74304411601.15$
$V_{34\,34} = 71215811623.43$,$V_{35\,35} = 75102931587.55$, $V_{36\,36} = 591160166.09$

$V_{37\,37} = 76260531711.57$,$V_{38\,38} = 494643760.95$, $V_{39\,39} = 358022904.78$

$V_{40\,40} = 81010993547.38$,$V_{41\,41} = 19166321628.81$, $V_{42\,42} = 84129188542.59$

$V_{43\,43} = 19984935211.97$,$V_{44\,44} = 16989476793.72$, $V_{45\,45} = 86011377521.47$

$V_{46\,46} = 1752936514.83$,$V_{47\,47} = 1318821516.70$, $V_{48\,48} = 88534524841.02$

$V_{49\,49} = 22154211422.67$,$V_{50\,50} = 725368555.24$, $V_{51\,51} = 992930391.64$

$V_{52\,52} = 877792906.90$,$V_{53\,53} = 730614823.93$, $V_{54\,54} = 15012854156.09$

$V_{55\,55} = 14910232324.45$

d. **Reconciled Data in Vector Matrix**

After applying all the generated matrix model of $\hat{x} = x - VA^T (AVA^T)^{-1} Ax$ into MATLAB software, the solution of the model which is the vector value of x^ in the form of 55 by 1 vector matrix

The vector matrix of $\hat{x}$ correspond to the reconciled values of flow rate and calculated enthalpy. All the new generated value of both reconciled value of flow rate and enthalpy are shown in a number of tables in the Appendix 4.

e. **Estimation of Temperature Data**

From the value of reconciled flow rate and enthalpy, the next step is to estimate back the value of temperature. The results of estimated temperature along with the reconciled values of flow rate and enthalpy are shown in the next part.

4.4 Reconciled Data of Crude Preheat Train

The results of reconciled values for all measurement data flow rates and calculated enthalpy in the whole system of heat exchanger network involve in this project are tabulated as below. All these results are obtained once the reconciliation model in matrix forms are written and successfully solved in MATLAB software.

As this project is still ongoing due to time contrain and limitation where the developed reconciliation model need to be checked in more details for their validity in the future, for the time being the results in the form of new generated reconciled value of measured flow rate and calculated enthalpy are well tabulated and shown *Table 8* and *Table 9* as in Appendix 4.

4.5 Data Analysis

The process of data analysis based on the results obtained from the reconciled values of both flow rate and enthalpy are done by comparing the obtained reconciled data with the raw measurement data and relate them with the mass and energy balance law.

From the results obtained, the new reconciled data by using the implementation of Bilinear Steady-State Data Reconciliation model should satisfy both the mass and energy balance equations involved in heat exchanger network system. The inlet and outlet flow rate for both cold and hot streams passing through each heat exchanger unit should satisfy the mass balance equation. Whereas, the energy balance equation should be satisfied by the value of reconciled enthalpy where the energy obtained by the cold streams is the same with energy loss by the hot streams in each heat exchanger unit.

Based on the obtained results from the treatment of both flow rate measurement and calculated enthalpies by the Bilinear Steady-State Data Reconciliation model, the reconciled values of enthalpy did satisfy the energy balance equations around each heat exchanger unit where the energy obtained in the form of heat obtained by the cold streams is the same with heat loss by the hot streams in each heat exchanger unit. This is proven by the Table 10 in Appendix 4.

Apart from that, the differences in reconciled values of enthalpy compared to the values of calculated enthalpy are very big. This is clearly shown through *Figure 4* below.

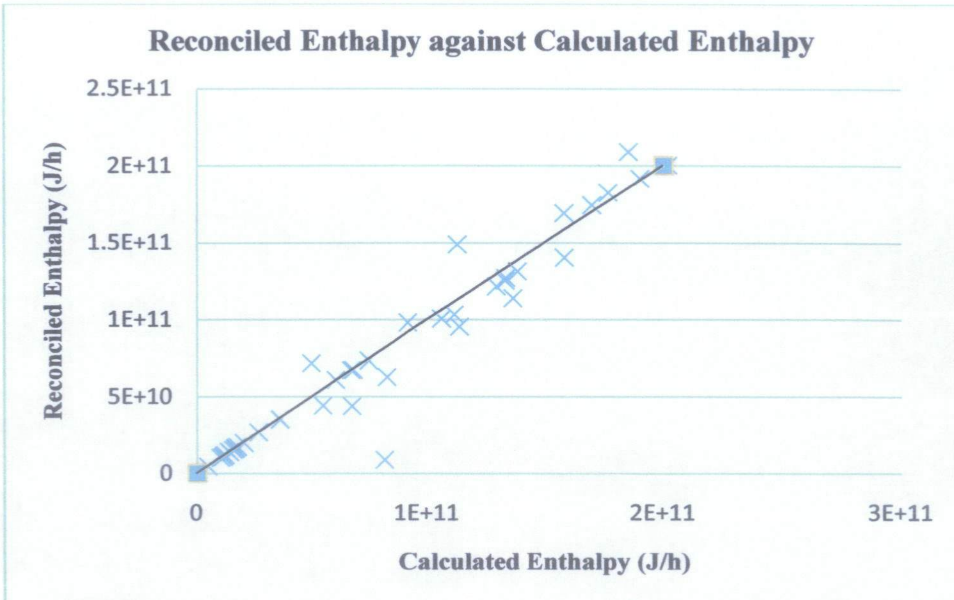

Figure 4: Reconciled Enthalpy against Calculated Enthalpy

The *Figure 4* here shows that the plotted points of reconciled enthalpy against calculated enthalpy are scattered around the 45° incline line. Some points are scattered far away from the line which show that the values of reconciled enthalpy differ much from their calculated values.

Apart from that, the results obtained on the reconciled values of flow rate give invalid values as they do not satisfy the mass balance equation around each heat exchanger unit and some of them have negative values. This can be shown through Figure 5 below of plotted points for values of reconciled flow rate against measured flow rate.

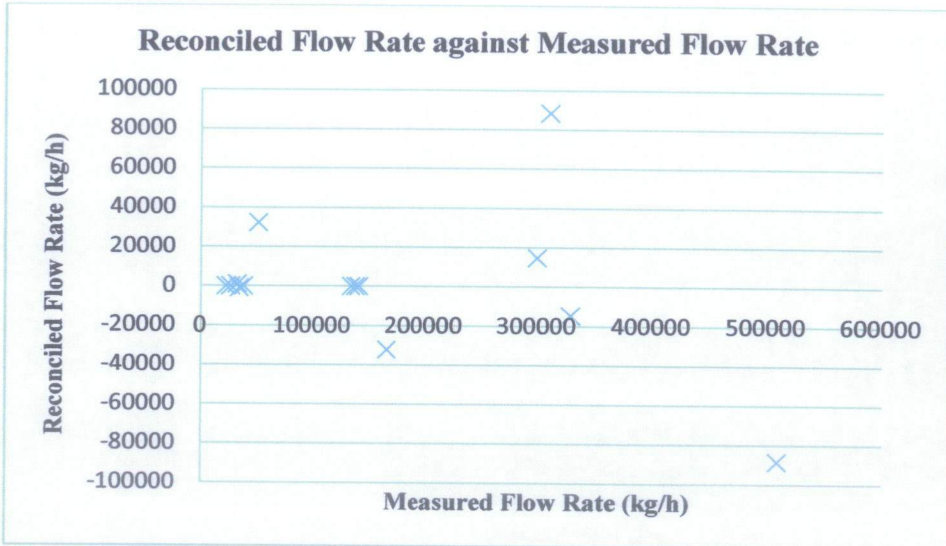

Figure 5: Reconciled Flow rate against Measured Flow rate

The plotted points of reconciled flow rate against measured flow rate are scattered around so randomly. The 45° incline line cannot be constructed to show the degree of differences in values between the reconciled flow rate and measured flow rate. This is due to the fact that even some of the points have negative values which are supposedly incorrect. Therefore, it can be said that the data obtained on reconciled values of flow rate are simply not valid and reliable.

Since the values are not valid, further estimation on temperature measurement cannot be done because they depend on the reconciled values of both flow rate and enthalpy which need to satisfy both mass and energy balance equaitons. Moreover, the value of remaining determinable unmeasured flow rate and temperatures also cannot be estimated as they depend on the value of reconciled flow rate and new estimated value of temperature measurement.

4.6 Discussion

All these invalid results of reconciled values of both flow rate and enthalpy are caused by some problems encountered and limitations that existed throughout the project which have been well identified.

First of all, some calculations involve throughout the procedure of developing data reconciliation model in the very beginning stage of data reconciliation procedure have utilized the crude and products properties that are less accurate. This is due to improper simulation through Petrosim software in the refinery plant to produce crude and products properties as there are some problems encountered during the simulation process. This has caused the improper way of developing Bilinear Steady-State Data Reconciliation model in which less accurate crude and products properties are used as part of the calculation procedure. Hence, the results obtained which consist of the values of reconciled flow rates and enthalpies are not valid and reliable.

In order to further improve the results obtained on the reconciled values of both flow rate and enthalpy, the simulation process by using Petrosim software need to be done properly so that more accurate crude and products properties can be obtained and used in developing the data reconciliation model to obtain more reliable and accurate values of reconciled values of flow rate and enthalpy before new temperature measurement can be further estimated as well as the determinable unmeasured flow rates and temperatures.

Afterthat, the developed Bilinear Steady-State Data Reconciliation model need to be rechecked for its functionality in a way that it can produce reconciled values of flow rate and enthalpy that satisfy both mass and enegy balance equations around the heat exchanger network after being solved by using Matlab software.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

After all, the application of data reconciliation is known to be very crucial. The Bilinear Steady-State Data Reconciliation Model approach is used to accomplish the procedure of data reconciliation of the bilinear steady-state system of HEN. In short, the measurement of stream flow rates and calculated enthalpy need to be reconciled simultaneously at first followed by the recalculation back of temperatures involve in the process of crude preheating. Then only all the determinable unmeasured flow rates and temperatures are estimated. Furthermore, the methodology of the project flow also has been well described and explained up until the results of reconciled values are obtained and data analysis. In a nut shell, one should always emphasized that, in today's highly competitive world market, resolving even a small error can lead to significant improvements in plant performance and economic values. The same concept does applied here in the heat exchanger network measurement data in the crude preheat train of refinery plant.

5.2 Recommendation

In order to further improve the results obtained from the treatment of both flow rate measurement and calculated enthalpy, some recommendations are suggested. All the recommendations are suggested base on the encountered problems and limitations that have already been highlighted in the previous section of this report. The recommendations to be implemented consist of proper way of simulation process in the refinery plant by using Petrosim software to produce more accurate and reliable crude and product properties which will then use as part of the calculation in developing the

Bilinear Steady-State Data Reconciliation model. Next, the Bilinear Steady-State Data Reconciliation model need to be recheck for its functionality in producing reconciled values of flow rate and enthalpy which supposedly satisfy all the mass and energy balance equations around all heat exchanger network.

REFERENCES

Bagajewicz, M.J. (n.d.). Data Reconciliation and Instrumentation Upgrade Overview and Challenges. Retrieved on 22 Jun 2013 from

http://cepac.cheme.cmu.edu/pasilectures/bagajewicz/Data%20Reconciliation%20and%20Instrumentation%20Upgrade.%20Overview%20and%20Challenges_FOCAPO(Bagajewicz)-03.pdf

Crowe, C.M. (1996). Data reconciliation – Progress and Challenges. 6 (2), 89-98.

Crowe, C.M., Garcia Campos, Y.A., & Hrymark, A. (1983). Reconciliation of Process Flow Rates by Matrix Projection, Part I: Linear Case. AIChe Journal. 29(1983), 881-888.

Crowe, C.M. (1989). Reconciliation of Process Flow Rates by Matrix Projection, Part II: Non-Linear Case. AIChe Journal. 22(1989), 616-623.

Ijaz, H., Ati, U.M.K., & Mahalec, V. (2013). Heat Exchanger Network Simulation, Data Reconciliation & Optimization. Applied Thermal Engineering. 52 (2013), 328-335.

Lid, T., Strand, S., & Skogestad, S. (2000). On-line optimization of a crude unit heat exchanger network. Retrieved on 27 July 2013 from http://www.nt.ntnu.no/users/skoge/prost/proceedings/cpc6-jan2002/lid.pdf

Narasimhan, S., & Jordanche, C. (2000). Data Reconciliation & Gross Error Detection. Houstan, Texas. Gulf Publishing Company.

Puming, Z., & Gang, R. (2002). Steady-State Bilinear Data Reconciliation Dealing with Scheduling. 15th Triennial World Congress, Barcelona, Spain.

Romagnoli, J.A.R., & Sanchez, M. C. (2000). Data Processing and Reconciliation for Chemical Process Operations. California. Academic Press.

Schraa, O.J., & Crowe, C.M. (1998). The numerical solution of bilinear data reconciliation problems using unconstrained optimization method. Computers & Chemical Engineering. 22(9), 1215-1228.

Smith, R. (2005). Chemical Process Design and Integration. West Sussex. John Wiley & Sons Ltd.

Yang, Y., Ten, R., & Jao, L. (1995). A Study of Gross Error Detection and Data Reconciliation in Process Industries. 19(95), 217-222.

APPENDICES

Appendix 1: Mass and Energy Balance Equation

a. Total Mass Balance Equations

E-1101:	$F_1 - F_3 = 0$	$F_4 - F_5 = 0$
E-1102:	$F_3 - F_6 = 0$	$F_{44} - F_8 = 0$
E-1103:	$F_6 - F_9 = 0$	$F_{10} - F_{11} = 0$
E-1104:	$F_9 - F_{12} = 0$	$F_{13} - F_{14} = 0$
E-1171:	$F_2 - F_{15} = 0$	$F_{16} - F_{17} = 0$
E-1105:	$F_{19} - F_{21} = 0$	$F_{22} - F_{10} = 0$
E-1106:	$F_{21} - F_{23} = 0$	$F_{24} - F_7 = 0$
E-1107:	$F_{23} - F_{25} = 0$	$F_{26} - F_{27} = 0$
E-1108:	$F_{25} - F_{28} = 0$	$F_{29} - F_{13} = 0$
E-1109:	$F_{28} - F_{30} = 0$	$F_{31} - F_{32} = 0$
E-1110:	$F_{30} - F_{33} = 0$	$F_{34} - F_{35} = 0$
E-1111:	$F_{33} - F_{36} = 0$	$F_{37} - F_{29} = 0$
E-1172:	$F_{20} - F_{38} = 0$	$F_{39} - F_{40} = 0$
E-1173:	$F_{38} - F_{41} = 0$	$F_{42} - F_{43} = 0$

b. Energy Balance Equations

E-1101:	$F_1h_1 - F_1h_3 + F_4h_4 - F_4h_5 = 0$
E-1102:	$F_1h_3 - F_1h_6 + (F_{24} + F_{39})h_{44} - (F_{24} + F_{39})h_8 = 0$
E-1103:	$F_1h_6 - F_1h_9 + F_{22}h_{10} - F_{22}h_{11} = 0$
E-1104:	$F_1h_9 - F_1h_{12} + F_{14}h_{13} - F_{14}h_{14} = 0$
E-1171:	$F_2h_2 - F_2h_{15} + F_{22}h_{22} - F_{22}h_{10} = 0$
E-1105:	$F_{19}h_{19} - F_{19}h_{21} + F_{22}h_{22} - F_{22}h_{10} = 0$
E-1106:	$F_{19}h_{21} - F_{19}h_{23} + F_{24}h_{24} - F_{24}h_7 = 0$
E-1107:	$F_{19}h_{23} - F_{19}h_{25} + F_{26}h_{26} - F_{26}h_{27} = 0$

Appendix 1: Mass and Energy Balance Equation (continue)

E-1108: $F_{19}h_{25} - F_{19}h_{28} + F_{14}h_{29} - F_{14}h_{13} = 0$

E-1109: $F_{19}h_{28} - F_{19}h_{30} + F_{32}h_{31} - F_{32}h_{32} = 0$

E-1110: $F_{19}h_{30} - F_{19}h_{33} + F_{34}h_{34} - F_{34}h_{35} = 0$

E-1111: $F_{19}h_{33} - F_{19}h_{36} + F_{14}h_{37} - F_{14}h_{29} = 0$

E-1172: $F_{20}h_{20} - F_{20}h_{38} + F_{39}h_{39} - F_{39}h_{40} = 0$

E-1173: $F_{20}h_{38} - F_{20}h_{41} + F_{42}h_{42} - F_{42}h_{43} = 0$

Appendix 2: Measurement of Flow Rates, Temperatures and Calculated Enthalpy

Table 5: Measured Flow Rate Data

Stream No.	Measured Flow (m^3/h)	Mass Density (kg/m^3)	Measured Flow (kg/h)
1	549.34	565.12	310443.55
2	89.35	565.12	50494.52
4	781.30	651.97	509386.23
14	182.70	734.59	134207.07
16	227.99	729.33	166282.19
18	638.69	565.12	360938.07
19	582.17	565.12	328996.67
20	56.52	565.12	31941.40
22	483.94	618.74	299434.14
24	39.24	665.71	26122.56
26	32.25	685.88	22121.27
32	211.61	652.86	138153.45
34	52.71	710.95	37470.72
39	50.86	665.71	33854.98
42	227.99	618.74	141069.53

Appendix 2: Measurement of Flow Rates, Temperatures and Calculated Enthalpy (Continue)

Table 6: Measured Temperature Data

Stream No.	Measured Temperature (°C)	Stream No.	Measured Temperature (°C)
1	41.56	23	144.98
2	33.09	24	220.48
3	63.00	25	150.76
4	152.36	26	267.83
5	143.38	27	164.50
6	77.61	28	172.49
7	162.95	29	283.30
8	82.54	30	185.37
9	94.04	31	278.45
10	166.00	32	228.96
11	142.24	33	192.73
13	216.02	34	331.30
14	143.38	35	245.53
15	122.48	36	202.17
16	175.22	37	326.80
17	141.52	38	154.13
18	120.34	39	220.48
19	123.79	40	180.38
20	123.79	41	156.77
21	140.85	42	175.22
22	192.57	43	172.85

Appendix 2: Measurement of Flow Rates, Temperatures and Calculated Enthalpy (Continue)

Table 7: Calculated Enthalpy

Stream No.	Calculated Enthalpy (J/h)	Stream No.	Calculated Enthalpy (J/h)
1	35922270000.92	24	15531842462.12
2	4651805969.52	25	138084326038.62
3	54451526337.64	26	16353147674.74
4	201926151544.65	27	10044246514.74
5	190027669247.11	28	157981324051.92
6	67073994919.03	29	105847325913.75
7	11479425361.12	30	169778742322.45
8	11852182958.03	31	111247490592.47
9	81277889844.20	32	91475364593.33
10	136301587020.18	33	176518647005.01
11	112542774119.03	34	35726522918.92
13	82235826195.85	35	26478114505.88
14	49368794422.99	36	185169288847.28
15	17217513979.08	37	133009377544.36
16	74384906353.56	38	13705417020.73
17	60077568963.57	39	20129352146.36
19	113383216182.30	40	16468591001.96
20	11008069750.62	41	13940735254.34
21	129002291785.86	42	67783480670.25
22	158125643931.14	43	66866502722.94
23	132784777922.03		

Appendix 3: Complete model of Incidence Matrix A and Covariance Matrix V.

a. **Incidence Matrix A:**

A = [24 x 55] matrix

A = [1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0
1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 -1 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0
0 0 0 0 0 0 0 1 0 -1 1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 -1 1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 -1 1
-1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 1 0 0 1 -1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 -1 1 -1 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0
1 0 -1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 -1 0 0 0 0 0 0 0 0 0 0 0 1 0 -1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 -1 1 -1 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 0 0 0 0 0 0 0 0 0
0 1 0 0 -1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 -1 1 -1 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 -1 1 -1 0 0 0 0 0
0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
-1 0 0 0 1 0 0 -1 1 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 -1 1 -1 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 -1 1 -1]

b. Covariance Matrix V:

V = [55 x 55] diagonal matrix

V = [602344.98 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 15935.60 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 1621714.59 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0; 0 0 0 112572.12 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 172811.05 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 676492.57 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0; 0 0 0 0 0 0 6376.58 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 560380.02 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 4264.93 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
0 0 0 0 0 0 0 0 0 3058.44 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 119289.85 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 8775.34 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0
0 0 0 0 0 0 0 0 0 7163.50 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 124378.83 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0
55251658125.86 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1451654734.38 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
56602052964.84 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 183601159627.15 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
179295200154.29 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 57839059644.72 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 412896524.80 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 59538323317.52
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 65875236525.68 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 15384843813.40 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 12445864698.04 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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1673261235.09 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0
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19014000497.69 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 71251443749.12 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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671612035.94 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 74304411601.15 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 494643760.95
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
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19984935211.97 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 16989476793.72 0 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
86011377521.47 0 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1752936514.83 0 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
1318821516.70 0 0 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 88534524841.02 0 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
22154211422.67 0 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 725368555.24 0 0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 992930391.64
0 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 877792906.90 0 0 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 730614823.93 0 0; 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 15012854156.09 0; 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 14910232324.45]

Appendix 4: Measurement Data of Flow Rate and Enthalpy After Treatment

Table 8: Measured and Reconciled Flow Rates of Crude Preheat Train

Stream No.	Measured Flow Rate (kg/h)	Reconciled Flow Rate (kg/h)
1	310443.55	88407.97
2	50494.52	32192.38
4	509386.23	-88407.97
14	134207.07	0
16	166282.19	-32192.38
19	328996.67	-14715.99
20	31941.40	955.17
22	299434.14	14715.99
24	26122.56	0
26	22121.27	0
32	138153.45	0
34	37470.72	0
39	33854.98	-955.17
42	141069.53	0

Appendix 4: Measurement Data of Flow Rate and Enthalpy After Treatment (Continue)

Table 9: Calculated Enthalpy and Reconciled Enthalpy of Crude Preheat Train

Stream No.	Calculated Enthalpy (J/h)	Reconciled Enthalpy (J/h)
1	35922270000.92	35453629869.81
2	4651805969.52	4593006395.23
3	54451526337.64	44274054360.68
4	201926151544.65	200368861239.93
5	190027669247.11	191548436749.06
6	67073994919.03	43903908566.42
7	11479425361.12	11559781198.72
8	11852182958.03	11929926992.99
9	81277889844.20	9041107747.41
10	136301587020.18	114056315069.57
11	112542774119.03	148919115888.59
13	82235826195.85	62757217393.67
14	49368794422.99	71798325141.08
15	17217513979.08	17285289770.37
16	74384906353.56	73540018348.82
17	60077568963.57	60847734973.68
19	113383216182.30	95485045934.08
20	11008069750.62	10805782394.88
21	129002291785.86	121665155241.19
22	158125643931.14	140236424376.68
23	132784777922.03	125430344975.06
24	15531842462.12	15324970932.60
25	138084326038.62	131357365467.11
26	16353147674.74	16131613401.82

27	10044246514.74	10204592909.78
28	157981324051.92	169328189856.39
29	105847325913.75	100728041782.95
30	169778742322.45	174458049342.45
31	111247490592.47	103333240392.21
32	91475364593.33	98203380906.16
33	176518647005.01	182660861096.01
34	35726522918.92	35129840320.43
35	26478114505.88	26927028566.87
36	185169288847.28	208983186745.01
37	133009377544.36	127050367431.96
38	13705417020.73	13903087780.38
39	20129352146.36	19830284749.38
40	16468591001.96	16732979363.88
41	13940735254.34	13961693632.99
42	67783480670.25	67352822720.65
43	66866502722.94	67294216868.04

Appendix 4: Measurement Data of Flow Rate and Enthalpy After Treatment (Continue)

Table 10: Comparison between reconciled enthalpy and calculated enthalpy

HE Unit	Stream No.	Calculated Enthalpy (J/h)	Reconciled Enthalpy (J/h)	Enthalpy Balance (J/h)
E-1101	3	54451526337.64150	44274054360.6828	8.82×10^{9}
	1	35922270000.91850	35453629869.8125	
	4	201926151544.6470	200368861239.931	8.82×10^{9}
	5	190027669247.1050	191548436749.061	
E-1103	9	81277889844.19590	9041107747.40636	3.49×10^{10}
	6	67073994919.02890	43903908566.4192	
	10	136301587020.1810	114056315069.572	3.49×10^{10}
	11	112542774119.0300	148919115888.585	
E-1105	21	129002291785.8620	121665155241.186	2.62×10^{10}
	19	113383216182.2960	95485045934.0826	
	22	158125643931.1440	140236424376.676	2.62×10^{10}
	10	136301587020.1810	114056315069.572	
E-1106	21	129002291785.8620	121665155241.186	3.765×10^{9}
	23	132784777922.0270	125430344975.064	
	7	11479425361.12420	11559781198.7226	3.765×10^{9}
	24	15531842462.1206	15324970932.5999	
E-1107	25	138084326038.6160	131357365467.107	5.93×10^{9}
	23	132784777922.0270		

			125430344975.064	
	26	16353147674.7383	16131613401.8237	5.93×10^{9}
	27	10044246514.7397	10204592909.7802	
E-1108	28	157981324051.9180	169328189856.391	3.79×10^{10}
	25	138084326038.6160	131357365467.107	
	29	105847325913.7540	100728041782.953	3.79×10^{10}
	13	82235826195.8510	62757217393.669	
E-1109	30	169778742322.4470	174458049342.449	5.13×10^{9}
	28	157981324051.9180	169328189856.391	
	31	111247490592.4650	103333240392.213	5.13×10^{9}
	32	91475364593.3321	98203380906.1553	
E-1110	33	176518647005.0050	182660861096.011	8.20×10^{9}
	30	169778742322.4470	174458049342.449	
	34	35726522918.9177	35129840320.4308	8.20×10^{9}
	35	26478114505.8818	26927028566.8683	
E-1111	36	185169288847.2780	208983186745.014	2.63×10^{10}
	33	176518647005.0050	182660861096.011	
	37	133009377544.3580	127050367431.956	2.63×10^{10}
	29	105847325913.7540	100728041782.953	
E-1171	15	17217513979.0805	17285289770.3697	1.27×10^{10}
	2	4651805969.51677	4593006395.22548	
	16	74384906353.5628	73540018348.8209	1.27×10^{10}
	17	60077568963.5654	60847734973.6767	
	38			

E-1172		13705417020.7313	13903087780.3804	3.097×10^9
	20	11008069750.6226	10805782394.8757	
	39	20129352146.3572	19830284749.3844	3.097×10^9
	40	16468591001.9590	16732979363.8797	
E-1173	41	13940735254.3441	13961693632.9939	5.86×10^7
	38	13705417020.7313	13903087780.3804	
	42	67783480670.2473	67352822720.65	5.86×10^7
	43	66866502722.9376	67294216868.0365	